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## A Critical Ionization Velocity Experiment on the ARGOS Satellite

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We report on a xenon gas release experiment conducted on the Advanced Research and Global Observations (ARGOS) Satellite in the F-region ionosphere above the European Incoherent Scatter (EISCAT) radar at Tromsø, Norway, Oct 20, 2000. In this experiment, xenon gas was released in the ram direction of the satellite. This was intended to induce ionization through the critical ionization velocity (CIV) process proposed by Alfvén in his theory of the formation of the planets in the solar system. If the CIV process had been operational and efficient, ionization of the xenon cloud might have been observed. Radar observations by EISCAT showed no detectable enhancement of the ambient plasma in the vicinity of the satellite. We present a simple model calculation which predicts that the overall yield of xenon ions in the release would be low, owing merely to the initially high density of the rapidly expanding xenon cloud. At the time of the experiment, the EISCAT mainland radars were in the final phase of a major upgrade. Thus full operations could not be guaranteed by the organization. As a result, the sensitivity of the radar was not too high at the time of our experiment. We also discuss some possible improvements for better radar observations of space releases testing the CIV hypothesis.

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## Nomenclature

$V^*$	= critical ionization velocity
$B$	= magnetic field
$E$	= electric field
$e$	= electron charge
$\eta$	= efficiency of ionization by CIV.
$M$	= molecular weight of the neutral gas
$n_{Xe}$	= density of neutral xenon gas
$n_{O^+}$	= density of oxygen ion
$\omega_c$	= charge exchange rate between neutral xenon and oxygen ion
$\omega_i$	= gyrofrequency of xenon ion
$\omega_{LH}$	= lower hybrid plasma mode time scale
$\sigma$	= cross-section of charge exchange between xenon and oxygen ion
$q_i$	= charge of ion
$\tau_H$	= electron heating time
$V_{Xe}$	= the component of the xenon gas velocity perpendicular to the magnetic field
$V_s$	= satellite velocity
$V_G$	= gas velocity relative to the satellite

## I. Introduction

Alfvén's hypothesis<sup>1</sup> of critical ionization velocity (CIV) is as follows. If a plasma and a neutral gas are traveling through each other across an ambient magnetic field, rapid ionization would occur if the relative velocity  $V$  perpendicular to the magnetic field exceeds a critical velocity  $V^*$  given by:

$$V^* = \sqrt{(2e\phi / M)} \quad (1)$$

where  $N$  is the ionization potential of the neutral gas species,  $e$  the electron charge, and  $M$  the molecular weight of the neutral gas. A cartoon of the CIV concept is shown in Figure 1.

CIV has been demonstrated repeatedly with relative ease in the laboratory. In the first CIV experiment using the homopolar device<sup>1</sup>, plasma and neutral gas filled the volume between two coaxial cylinders. An **EXB** field was applied between the cylinders, driving the plasma through the neutral gas. As the plasma velocity exceeded a critical value, the neutral gas was indeed ionized. The critical value observed was slightly above but very close to the  $V^*$  given by eq(1). The ionization observed in this experiment was nearly 100% in  $3 \mu s$ <sup>1</sup>. Subsequent laboratory experiments using coaxial plasma guns [for example, Ref.2] demonstrated CIV repeatedly with ease. For reviews of CIV experiments in the laboratory, see Refs 3,4.

CIV could be relevant to practical space situations. Spacecraft orbital velocities often exceed the value of  $V^*$  for some species of the exhaust gases. If spacecraft exhaust gases can undergo CIV ionization, there would be important implications. For example, the ionized species can cause contamination on the instruments onboard and characteristic optical or spectral emissions can be present in the vicinity of the spacecraft.

However, no CIV experiments in space has ever achieved any ionization yield above a few percent, in contrast to the nearly 100% ionization found in the laboratory CIV results. Furthermore, the scant ionization that occurs in the CIV space experiments may be due to non-CIV processes, like charge exchange, thermal ionization, associative ionization, etc.<sup>5</sup>. These experiments used remote optical or in-situ probe methods to detect possible enhanced ionization by CIV. For reviews on CIV space experiments, see Refs 3,4.

No space CIV experiment using radars to measure the possible enhancement of ions in the spacecraft vicinity has been reported previously. Unlike *in-situ* plasma probes, radar measurements can observe ionization over the entire expanding gas cloud instead of just one point in the cloud at one time. Unlike ground optical measurements, radars are not limited by background optical contamination and are therefore more sensitive.

## II. Cyclic Process of CIV

The basic CIV mechanism is as follows (Figure 2). When a magnetized plasma and a neutral gas are in relative motion through each other, the kinetic energy is converted into plasma wave energy, energizing electrons which ionize the gas. The ions have much larger gyro-radii than the electrons. If the ionization rate is much faster than the

gyrofrequency, the newborn ions appear to be beam-like. The plasma beam traverses the magnetic field, exciting plasma instabilities in a time scale less than the ion gyro-period. The instability generates plasma waves which result in energization of the electrons at the expense of ion kinetic energy<sup>6</sup>.

In the quasi-linear formulation of ion beam-plasma interaction, the energized electrons form a hot tail distribution. They may ionize the neutrals by electron impact. Upon ionization, a newborn ion will travel at nearly the same velocity of the neutral and will carry on the next cycle of conversion from kinetic energy to waves energy, then to electron energy, and then to impact ionization energy, and so on.

### III. Design of the CIV Experiment

In the CIV experiment on the Advanced Research and Global Observations (ARGOS) Satellite, xenon gas was released in the ram direction from the satellite in the ionosphere. A feasibility study of this experiment had been presented<sup>7</sup>.

The experiment took place in sunlight at about 11:00 L.T., 800 km altitude, and over the EISCAT radar, Tromsø, Norway, Oct 20, 2000 [Figure 3]. The ionization potential of Xe is 12.13 eV, whereas the dominant line, Lyman Alpha ( $\text{Ly}\alpha$ ) of sunlight has energy of about 10.2 eV. Therefore, photo-ionization of Xe is ruled out. Since the excited states of Xe do not match in energy with  $\text{Ly}\alpha$ , photo-ionization of xenon via the metastable states is not likely<sup>8</sup>.

The satellite velocity  $V_S$  was about  $7.4 \text{ km s}^{-1}$  and the gas velocity  $V_G$  about  $0.2 \text{ km s}^{-1}$  relative to the satellite. The ambient magnetic field was  $13^\circ$  from the vertical [Figure 4]. The perpendicular (to the magnetic field) component  $V_{Xe}$  of the gas velocity was given by

$$V_{Xe} = (V_S + V_G) \cos 13^\circ = 7.4 \text{ km.s}^{-1} \quad (2)$$

Since xenon mass 131.3 AMU and its ionization potential 12.13 eV, its critical ionization velocity (eq.1) is given by  $V^* = 4.225 \text{ km.s}^{-1}$ . Thus,  $V_{Xe}$  (eq.2) exceeded  $V^*$  by a large margin. That is, the gas velocity met the basic requirement (eq.1) for CIV to occur.

For a cold gas release, charge exchange between the neutral gas atoms and the ambient plasma ions gives the seed ions.



Since ions gyrate in a magnetic field with a gyro-frequency  $\omega_i$ , the frequency  $\omega_c$  of ions generated by charge exchange must exceed  $\omega_i$  in order to be beam-like. The charge exchange frequency  $\omega_c$  is given by

$$\omega_c = n_{Xe} \sigma V_{Xe} n_{O^+} \quad (4)$$

where  $\sigma$  is the charge exchange cross section,  $n_{Xe}$  the xenon gas density, and  $n_{O^+}$  the ambient oxygen ion density. Taking  $\sigma \approx 4.8 \times 10^{-16} \text{ cm}^2$  [See Ref.9],  $n_{Xe} \approx 10^9 \text{ cm}^{-3}$  at one second after release<sup>7</sup>, and  $n_{O^+} \approx 2 \times 10^4 \text{ cm}^{-3}$  at 800 km altitude in daytime, we obtain

$$\omega_c \approx 7.48 \times 10^3 \text{ s}^{-1} \quad (5)$$

For comparing time scales, we do not use  $2\pi$  factor in eq(5). The ion gyro-frequency  $\omega_i$  for the new-born beam ions traveling at  $7.4 \text{ km s}^{-1}$  in an ambient magnetic field  $B$  of 0.54 G is

$$\omega_i = q_i B / M = 6.25 \text{ Hz} \quad (6)$$

The charge exchange frequency,  $7480 \text{ s}^{-1}$  in eq(5), exceeds the gyro-frequency  $\omega_i$  (eq.6) by a good margin.

$$\omega_c \gg \omega_i \quad (7)$$

Formisano *et al.*<sup>10</sup> found that if the inequality eq(7) is reversed, the efficiency  $\eta$  of CIV would drop to  $\eta \approx 0.025$ . If eq(7) is satisfied, the ion formation is beam-like. The beam-plasma interaction generates lower hybrid instability which heats the electrons<sup>11,12</sup> forming a hot tail in a time scale  $\tau_H$  given by Tanaka and Papadopoulos<sup>6</sup>.

$$\tau_H \approx 30 \omega_{LH}^{-1} \quad (8)$$

where  $\omega_{LH}$  is the lower hybrid frequency. For xenon CIV experiments in the ionosphere, the lower hybrid frequency  $\omega_{LH} \approx 1034 \text{ Hz}$ <sup>13</sup>, which translates into a heating time  $\tau_H \approx 27 \text{ ms}$ . This means that electron heating can occur well within the ion gyro-period, and well within the temporal confines of the experiment itself, which is a few seconds. Therefore, the time scales necessary for CIV to occur in the ARGOS experiment are satisfied.

If CIV occurred, the ionization level in the xenon gas in the vicinity of the satellite must be elevated. We used the EISCAT radar to attempt to detect any elevated ionization level relative to the background plasma.

#### IV. EISCAT Radar Results

Figure 5 shows the signal from the satellite for the three alternating code pulses, for the short pulse and for the decoded alternating code in 1.5 km range resolution. The satellite passed the beam in 5-6 seconds, not so far from the estimated 3-4 seconds. The actual passing time depends on the direction in which the satellite passes the beam, since the VHF antenna pattern is asymmetric in E-W and N-S planes. This figure shows echoes from the satellite in different modes. No enhanced ionization is detected on the ram or wake sides of the spacecraft.

The null results mean that either the experiment failed to produce CIV ionization of the xenon neutral cloud to any appreciable extent, or that the experiment was not sensitive enough to detect the increased electron density produced though CIV. The ionized cloud should have been visible, had a CIV discharge taken place. The radar beam was about 20km x 20km wide at the satellite altitude. The Xe ion gyroradius was 188 m. In 3 sec, the ions would have gyrated out and in the neutral cloud several times, as observed in the detailed simulations of Brenning et al.<sup>14</sup>. The xenon ion cloud would essentially be within the radar beam in 3 seconds after the release.

#### V. Summary and Recommendation for Future EISCAT Observations

Alfvén's CIV hypothesis has been demonstrated repeatedly with ease in the laboratory. Indeed, laboratory experiments showed that rapid ionization occurred when the perpendicular component of the relative velocity between a neutral gas and a plasma exceeded a critical velocity. The value of the critical velocity observed was near but slightly higher than that given by Alfvén's formula, eq(1). On the other hand, the experiments for testing CIV in space have produced results of low to negligible ionization yields only. Even the source of ionization in the CIV space experiments was questionable. However, if CIV occurs in space, it would be significant. If CIV really exists, it should be regarded as a fundamental property in plasma physics and has potentially important applications.

Previous attempts to test CIV by means of gas releases from spacecraft failed to demonstrate any significant enhancement of ionization. Not only the *in situ* plasma probes detected slight depletion (instead of enhancement) of ionization when the gas was released in the ram direction, but also there was slight enhancement when the releases were in the wake direction<sup>4, 15</sup>. Optical measurements from the ground also failed to detect any enhanced ionization during gas releases from spacecraft<sup>16</sup>.

In the CIV experiment onboard the ARGOS satellite, xenon gas was released in the ram direction at an altitude of about 840km above the EISCAT radar, Tromsø, Norway. The satellite velocity was about 7.4 km/s in an almost horizontal direction while the ambient magnetic field at that location was only 13° off the vertical. The perpendicular component of the xenon velocity exceeded the xenon critical ionization velocity. The xenon velocity satisfied the basic requirement for CIV to occur. Ionization by sunlight was impossible because the ionization potential of xenon is higher than the energy of the solar Lyman Alpha UV line. Unlike barium, which was used in some previous CIV tests in space, xenon is not likely to undergo associative ionization. Therefore, any enhanced ionization during the gas release must be attributed to CIV.

EISCAT did not detect any enhanced ionization in the critical ionization velocity experiment on the ARGOS satellite on October 20, 2000. The very low transmitter power of EISCAT was caused by the upgrading work during the time of our observations. Since then, the radar has been upgraded successfully.

Because the upgraded radar receiver will have dynamic range exceeding 50 dB, it might be possible to distinguish clearly whether there will appear ionization caused by the CIV process above and around the satellite echo. A few simultaneous observations with the UHF and VHF radars, when the satellite is straight above or a little north of the radar site, would be optimal to see the process at both 930 and 224 MHz, with the VHF antenna still divided into two sub-radars. Another desirable configuration would be a measurement along the magnetic field line when the satellite passes slightly south of the radar site. This is possible only with 930 MHz system, but it would reveal if there would be any preferable alignment of the ionization along the magnetic field line. We also refer to the challenges of a new multistatic phased array EISCAT VHF radar under the design study phase (<http://www.eiscat.se/>). In the future the phased array EISCAT radar could make much more precise observations on the CIV process.

## Appendix. Spherical Cloud Model

We examine a simple model<sup>17</sup> of the expansion of a spherical gas cloud. The initial number of Xe atoms was about  $10^{24}$  atoms and a reasonable estimate for the radial expansion velocity is 200 m/s<sup>18</sup>. Figure 6 shows the density of the ion cloud using these parameters, at various times after the release. We have shown curves assuming 100% ionization of the Xe (as is obtained in laboratory CIV experiments) and 10% ionization. This is a reasonable bound since, if the ionization is only 1%, one would say that it was a "failed" CIV experiment anyway. (Note: A more careful expansion formula<sup>19</sup> was used in Ref.18 but did not change the physical features and conclusions of the ionization yield model.)

## Acknowledgment

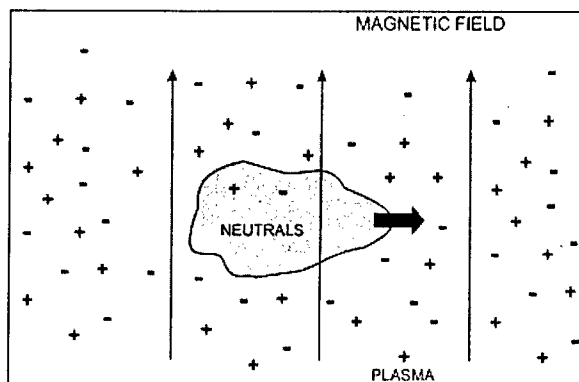
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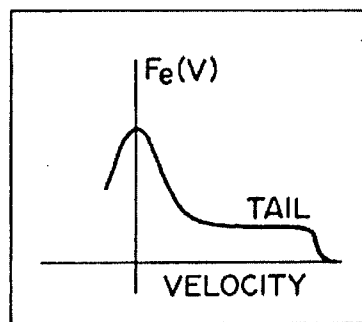
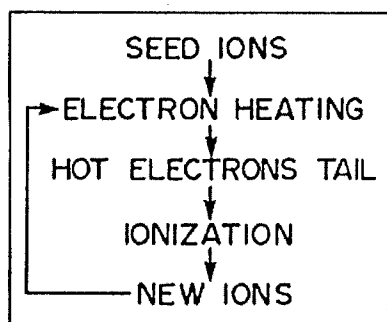
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TABLE 1

Parameter	Value
Xenon mass	131.3 AMU
Xenon ionization potential	12.13 eV
Xenon critical ionization velocity $V^*$	4.225 km/s
Altitude	840 km
Ambient $O^+$ density	$5 \times 10^4 \text{ cm}^{-3}$
Ambient electron density	$10^5 \text{ cm}^{-3}$
Magnetic field magnitude	0.54 G
Magnetic field declination	$13^\circ$
Magnetic field inclination	$77^\circ$
Electron frequency	$10^6 \text{ Hz}$
Xenon gyrofrequency	6.2 Hz
Xenon gyroradius	188 m
Xenon lower hybrid frequency	3 kHz
Satellite velocity	7.4 km/s
Satellite altitude	800 km
Satellite orbit inclination	$98.7^\circ$
Gas pressure at nozzle	$10^7 \text{ gm/cm}^2$
Gas temperature	$0^\circ\text{C}$
Gas mass release rate	280 gm/s
Gas number release rate	$1.27 \times 10^{24} / \text{s}$
Gas velocity relative to the satellite	200 m/s

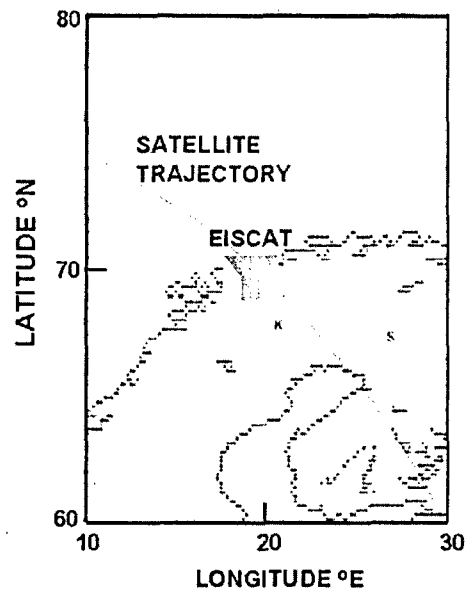


**Figure 1.** A schematic diagram of neutral gas traveling through a magnetized plasma.

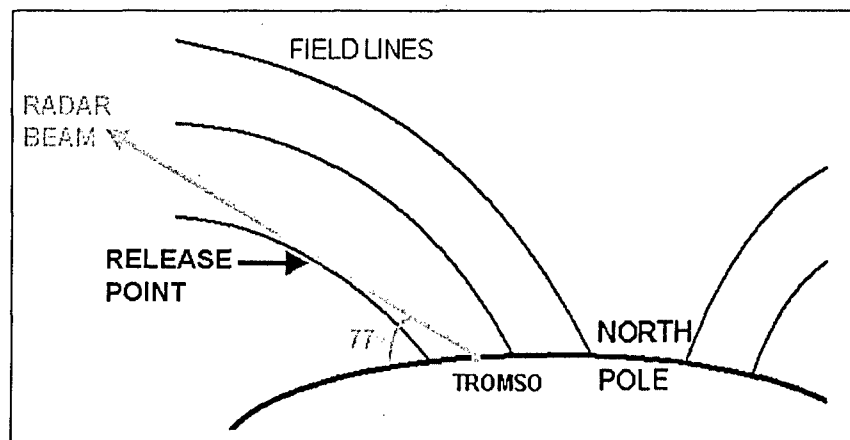


**Figure 2.** (Left) Cyclic process of CIV. (Right) Plateau tail in the electron velocity distribution.





**Figure 3.** Map showing the satellite trajectory over the EISCAT radar, Tromsø, Norway.



**Figure 4.** The near horizontal satellite velocity and near vertical magnetic field over the EISCAT radar, Tromsø, Norway.

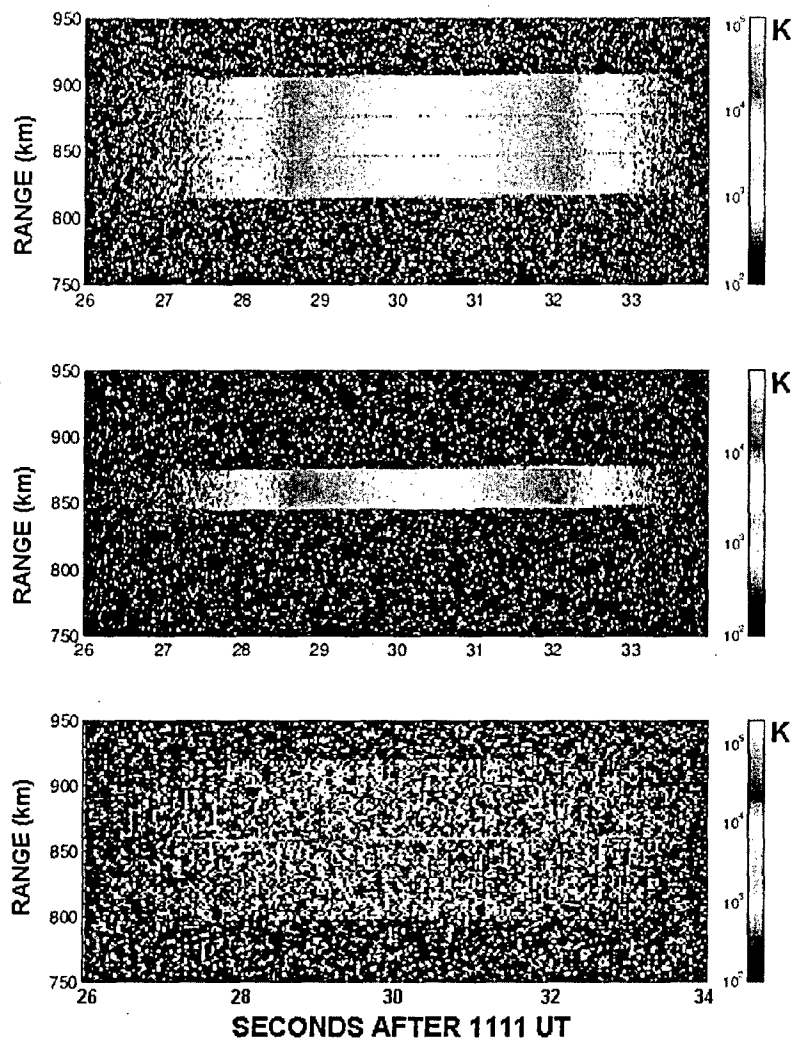
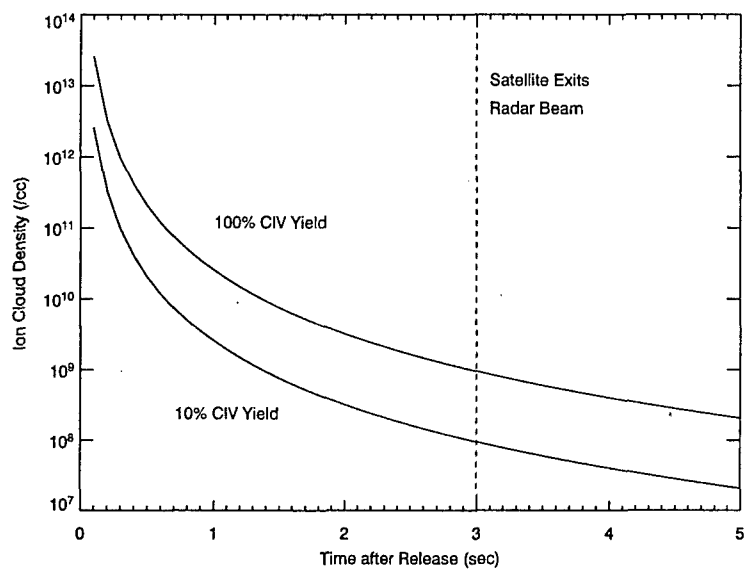


Figure 5. EISCAT radar echoes from ARGOS. No enhanced ionization was detected.



**Figure 6.** Density of the Xe ion cloud with a spherical expansion velocity of 200 m/s relative to the satellite. The dashed line shows the time after release when the satellite moves out of the radar beam.